Available online at www.sciencedirect.com

ScienceDirect

Journal of Hydro-environment Research 8 (2014) 421−427

Journal of Hydro-environment Research

www.elsevier.com/locate/jher

Short communication

Experimental study on the validity of flow region division

Shu-Qing Yang [a], Yu Han [a], Pengzhi Lin [b], Changbo Jiang [c], Robert Walker [a,*]

[a] *School of Civil, Mining and Environmental Engineering, Univ. of Wollongong, NSW 2522, Australia*
[b] *State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, Sichuan 610065, PR China*
[c] *Changsha University of Science and Technology, Changsha, Hunan 410114, PR China*

Received 9 September 2012; revised 19 November 2013; accepted 19 November 2013
Available online 18 December 2013

Abstract

Einstein first proposed that a river flow can be divided into three parts, corresponding to the banks and its bed, respectively, but he did not explain why the flow is dividable and how to divide the flow, in other words the flow division is only a mathematical treatment to simplify his analysis. Since Einstein's proposition there have been many researches and debates on this topic, many division lines have been proposed, but there is no specially designed experimental research to verify the physical existence of division lines, and these division lines have not been tested against the experimental data. For this purpose, an experiment in a rectangular open channel was conducted to measure whether zero-shear stress exists in an open channel except its existence on the free surface. The measured results reveal that zero-shear stress indeed exists below the free surface, and some proposed equations of division line agree well with the profile of the measured zero-shear line, thus it is clarified that Einstein's hypothesis is not only useful to simplify the mathematical treatment, but also it has the physical basis, i.e., zero-shear division line. As far as the authors know, in the literature, this is the first experimental proof that the division lines indeed exist in channel flows.

Keywords: Division line; Boundary shear stress; 3-D flow division; Reynolds shear stress; Secondary currents

1. Introduction

In river and environmental engineering, the method of flow division has been often used to estimate sediment transport, boundary shear stress and to eliminate the side wall effects. If the flow region can be accurately partitioned, the bed and side-wall shear stress may be separated from the total shear stress (Yang and Tan, 2008). For this reason, partitioning flow is very important in studies of bed-load transport, channel migration of bank erosion. The physical existence of division lines in open channel and closed duct flow is of great interest to a wide range of people.

Leighly (1932) first proposed that a channel could be split into sub-regions by division lines crossing the isovels orthogonally. He pointed out that in the absence of secondary currents, the boundary shear stress acting on the bed must be balanced by the downstream component of the weight of water contained within the bounding orthogonals. Keulegan (1938) also contributed to the early development of this subject. He suggested that the flow region should be partitioned with straight division lines which bisected the base angles. Einstein (1942) probably is the first one who believed that river flows are also dividable, after him the hydraulic radius separation method has been widely used in practical studies and engineering practice. He suggested that the flow region could be divided into three sub-sections, two for side walls and the other for the bed. Unfortunately, Einstein and others did not provide any theoretical explanation why the flow region is dividable or how it is divided. Chien and Wan (1999) attempted to explain Einstein's method in terms of the energy transport mechanism, stating that the energy present in each of the flow regions would be transferred as heat at the boundary. This mechanism has received little attention from researchers and academics since its publication.

* Corresponding author.
E-mail address: shuqing@uow.edu.au (R. Walker).

1570-6443/$ - see front matter © 2014 International Association for Hydro-environment Engineering and Research, Asia Pacific Division. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jher.2013.11.001

Since the 1990s, several division line theories have been proposed by Daido (1992), Yang and Lim (1997, 1998, 2002, 2005) and Guo and Julien (2005), which have considerably advanced our understanding of flow partitioning. Although the concept of flow division is widely accepted, there are several differing methods of calculating division lines. Daido (1992) attempted to use the Prandtl–Karman equation to obtain an expression for the division line in a rectangular open channel, developing two different configurations depending on the aspect ratio. Interestingly, the division line obtained by Daido's method produces a concave shaped boundary shear stress distribution on the side wall which is contradictory to the experimental findings of Knight and Harish (1985). Yang and Lim (1997, 1998, 2002, 2005) hypothesised that turbulent energy must be transported through the minimum relative distance to the boundary. This model divides the flow in a rectangular or trapezoidal channel with linear lines. This theory does not account for the effects of secondary currents and was validated with experimental data. Guo and Julien (2005) developed the first approximation of the division line expression, following this study, Yang and Lim (2006) advanced the theory of Guo and Julien by deriving the second approximation of their division line expression. All proposed methods of partitioning flow proposed are mathematical treatments only and are not based on experimental data, some of them believe that the flow can be divided by straight lines, e.g., Keulegan (1938); Yang and Lim (1997); others use curves to divide the flow region, i.e., Leighly (1932), Chien and Wan (1999), Daido (1992), Guo and Julien (2005), Yang et al. (2005).

Obviously, there is a debate in the research community whether the division line is only a mathematical method or the flow is really dividable from the physical point of view; the debate can be also extended to whether a rectangular and trapezoidal channel is divided by straight line or curves. Researchers and engineers are keen to know which model in the literature can yield the best agreement with the experimental data. The purpose of this study is to experimentally test if rectangular open channel flow can be partitioned, and if so, how to determine the physical meaning of the division line? Additionally, it is important to identify whether the division lines are linear or curved. In this study, experimentally obtained data recorded by 2D LDA system specifically for this study as well as data from previous research by Melling and Whitelaw (1976) and Tracy (1965) will be analysed as they did not report whether the flow region is dividable from their experiments.

2. Review of existing division lines

The following section provides a brief review of the existing division line theories which have been considered in this study. The division lines proposed by the previous researchers are:

Keulegan Method (KM): Keulegan (1938) proposed that the flow in a polygonal channel should be separated into three areas by division lines bisecting the base angles as shown in Fig. 1. Unfortunately, no theoretical explanation was given.

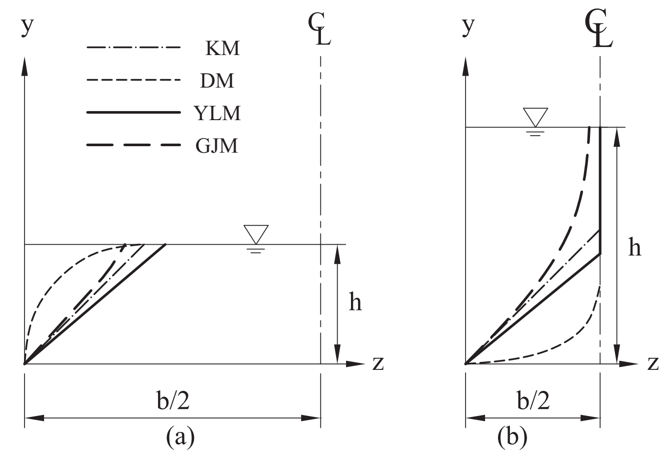

Fig. 1. Division lines as proposed by previous researchers, (a) b/h $\geq \alpha$; (b) b/h $\leq \alpha$, in which KM stands for Keulegan's method; DM for Daido's method, YLM for Yang and Lim's method, GJM for Guo and Julien.

Daido Method (DM): Daido (1992), performed extensive research in order to derive an equation for the division line in a rectangular open channel flow. Utilising the Prandtl–Karman equation, he proposed that the velocity at the division line could be calculated using the log-law from the bed and side wall as follows

$$\frac{u_1}{\overline{u_{*_b}}} = \frac{1}{\kappa}\ln\left(\frac{9\overline{u_{*_b}}y}{\nu}\right) \tag{1}$$

$$\frac{u_2}{\overline{u_{*_w}}} = \frac{1}{\kappa}\ln\left(\frac{9\overline{u_{*_w}}z}{\nu}\right) \tag{2}$$

where u_1 and u_2 are the velocity valid in the bed and side wall regions, he assumed that the condition of division line should be $u_1 = u_2$. $\overline{u_{*_b}}$ and $\overline{u_{*_w}}$ are the shear velocities on the bed and side walls, respectively, κ is the Karman constant and ν is the kinematic viscosity.

On the division line $u_1 = u_2$ must be satisfied, thus one can obtain the following relationship

$$\alpha = \frac{\overline{u_{*_b}}}{\overline{u_{*_w}}} \tag{3}$$

$$z = \frac{\left(9\overline{u_{*_b}}/\nu\right)^{\alpha}}{9\overline{u_{*_w}}/\nu}y^{\alpha} \tag{4}$$

Guo and Julien Method (GJM): Guo and Julien (2005) determined the bed and side wall shear stresses in a rectangular open channel flow through the solving of the continuity and momentum equations. Conformal mapping was used to partition the flow and the following relationship was derived:

$$\frac{\pi z}{2b} = \tan^{-1}\exp\left(-\frac{\pi y}{b}\right) \tag{5}$$

where b is the channel width.